U.S. Department
of Transportation
**Federal Aviation
Administration**

Advisory Circular

Subject: AEROELASTIC STABILITY SUBSTANTIATION OF TRANSPORT CATEGORY AIRPLANES

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Change:

1. PURPOSE. This advisory circular (AC) provides guidance material for acceptable means, but not the only means, of demonstrating compliance with the provisions of part 25 of the Federal Aviation Regulations (FAR) dealing with the design requirements for transport category airplanes to preclude the aeroelastic instabilities of flutter, divergence and control reversal. The precise detailing of analytical procedures and testing techniques is beyond the scope of this AC. Some general considerations are set forth herein, with supportive discussion, to be considered in demonstrating compliance with § 25.629 and related regulations.

2. CANCELLATION. Advisory Circular 25.629-1, Flutter Substantiation of Transport Category Airplanes, dated January 4, 1985, is cancelled.

3. RELATED FAR SECTIONS.

§ 25.251 - Vibration and buffeting.
§ 25.305 - Strength and deformation.
§ 25.335 - Design airspeeds.
§ 25.343 - Design fuel and oil loads.
§ 25.571 - Damage-tolerance and fatigue evaluation of structure.
§ 25.629 - Aeroelastic stability requirements.
§ 25.631 - Bird strike damage.
§ 25.671 - General (Control Systems).
§ 25.672 - Stability augmentation and automatic and power-operated systems.
§ 25.1309 - Equipment, systems and installations.
§ 25.1329 - Automatic pilot system.
§ 25.1419 - Ice protection.

4. BACKGROUND.

a. Flutter and other aeroelastic instability phenomena have had a significant influence on airplane development and the airworthiness criteria governing the design of civil airplanes. The initial requirement for consideration of flutter was minimal in the

1931 "Airworthiness Requirements of Air Commercial Regulations for Aircraft," Bulletin No. 7-A. The airplane flutter requirement specified that "no surface shall show any signs of flutter or appreciable vibration in any attitude or condition of flight." In 1934, Bulletin No. 7-A was revised in view of service experience and contained advice and good practice techniques for the early airplane designer regarding flutter prevention measures. All airplane designs were required to have interconnected elevators, statically-balanced ailerons, irreversible or balanced tabs, and, in some cases, a ground vibration test was required to be conducted.

b. Regulations dealing specifically with flutter, deformation, and vibration on transport category airplanes were first introduced when part 04 of the Civil Air Regulations (CAR) became effective in the mid-1940's. The criteria related the solution of the flutter problem to frequency ratios based on model tests conducted by the Army Air Corps. Also, based on the Army Air Corps developments, part 04 imposed a design factor of 1.2 on equivalent airspeed to provide a stiffness margin for the airframe. In addition to this empirical approach, and recognizing the advancing state-of-the-art, part 04 referenced publications containing developing flutter theory.

c. The flutter requirement of part 04 evolved into CAR 4b.308 where developing fail-safe philosophy continued to change the scope of flutter substantiation. Among these developments was a revision to CAR 4b.320 in 1956 to require fail-safe tabs and a revision to CAR 4b.308 in 1959 to require fail-safe flutter damper installations. The flutter requirement was extensively revised in 1964 to require compliance with the single failure criteria for the entire airplane as well as adding special provisions for turboprop airplanes.

d. Service experience indicated that single failure criteria related to flutter stability were not sufficiently objective and comprehensive to cover modern, complex, transport airplanes equipped with highly redundant systems. Therefore, part 25 of the FAR, which was recodified from part 04b of the CAR, was amended to require that, unless combinations of failures are shown to be extremely improbable, they must be considered in design for freedom from flutter and divergence.

e. The development of speed and attitude limiting systems has created the need for a minimum speed margin for fail-safe aeroelastic stability substantiation. Part 25 as amended at Amendment 77 incorporated this minimum fail-safe speed boundary, revised the safety margins for aeroelastic stability, and expanded the list of failures, malfunctions and adverse conditions that needed to be addressed.

f. Additional regulations governing the interaction of systems with structures have been written for airplanes with advanced electronic flight control systems. These regulations prescribe variations in the fail-safe speed margins depending on the probability of system failure.

5. DISCUSSION OF REQUIREMENTS. The general requirement for demonstrating freedom from aeroelastic instability is contained in § 25.629, which also sets forth specific requirements for the investigation of these aeroelastic phenomena for various airplane configurations and flight conditions. Additionally, there are other conditions defined by the sections of the FAR listed in paragraph 3 above to be investigated for aeroelastic stability to assure safe flight. Many of the conditions contained in this AC pertain only to certain specific amendments of the FAR. Type design changes to airplanes certified to an earlier part 25 amendment must meet the certification basis established for the modified airplane.

a. Aeroelastic Stability Envelope.

(1) For nominal conditions without failures, malfunctions, or adverse conditions, freedom from aeroelastic instability is required to be shown for all combinations of airspeed and altitude encompassed by the design dive speed (V_D) and design dive Mach number (M_D) versus altitude envelope enlarged at all points by an increase of 15 percent in equivalent airspeed at both constant Mach number and constant altitude. Figure 1A represents a typical design envelope expanded to the required aeroelastic stability envelope. Note that some required Mach number and airspeed combinations correspond to altitudes below standard sea level.

(2) The aeroelastic stability envelope may be limited to a maximum Mach number of 1.0 when M_D is less than 1.0 and when there is no large and rapid reduction in damping as M_D is approached.

(3) Some configurations and conditions that are required to be investigated by § 25.629 and other part 25 regulations consist of failures, malfunctions or adverse conditions. Aeroelastic stability investigations of these fail-safe conditions need to be carried out for all approved altitudes to the greater airspeed defined by:

(a) The V_D/M_D envelope determined by § 25.335(b); or,

(b) An altitude-airspeed envelope defined by a 15 percent increase in equivalent airspeed above V_C at constant altitude, from sea level up to the altitude of the intersection of 1.15 V_C with the extension of the constant cruise Mach number line, M_C, then a linear variation in equivalent airspeed to M_C + .05 at the altitude of the lowest V_C/M_C intersection; then at higher altitudes, up to the maximum flight altitude, the boundary defined by a .05 Mach increase in M_C at constant altitude.

Figure 1B shows the minimum aeroelastic stability envelope for fail-safe conditions, which is a composite of the highest speed at each altitude from either the V_D envelope or the constructed altitude-airspeed envelope based on the defined V_C and M_C.

Fail-safe design speeds, other than the ones defined above, may be used for certain system failure conditions when specifically authorized by other rules or special conditions prescribed in the certification basis of the airplane.

FIGURE 1A. MINIMUM REQUIRED AEROELASTIC STABILITY MARGIN

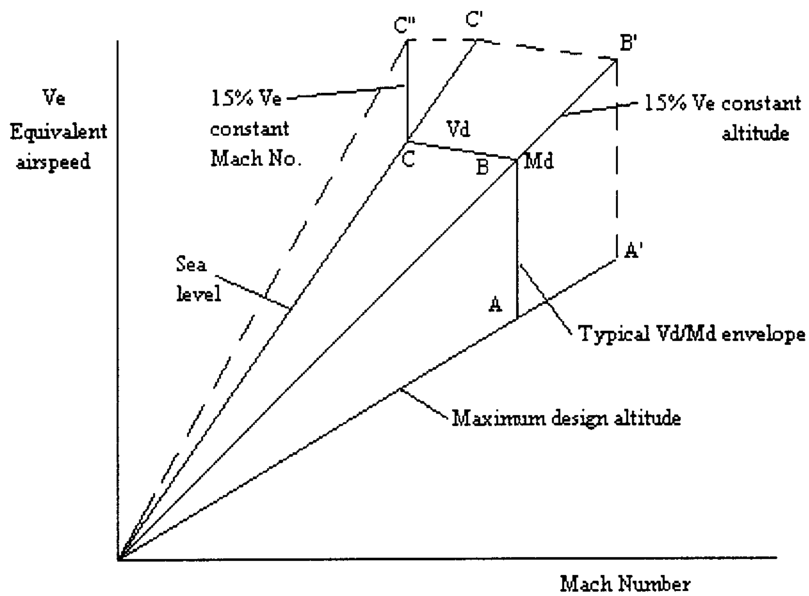
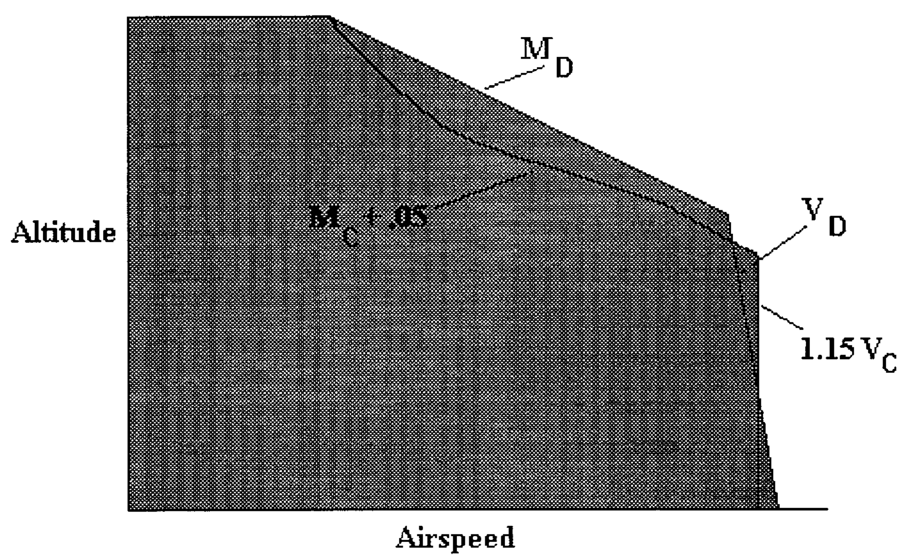


FIGURE 1B MINIMUM FAIL-SAFE CLEARANCE ENVELOPE



b. Configurations and Conditions. The following paragraphs provide a summary of the configurations and conditions to be investigated in demonstrating compliance with part 25. Specific design configurations may warrant additional considerations not discussed in this AC.

(1) Nominal Configurations and Conditions. Nominal configurations and conditions of the airplane are those that are likely to exist during normal operation. Freedom from aeroelastic instability should be shown throughout the expanded clearance envelope described in paragraph 5a(1) above for:

(a) The range of fuel and payload combinations, including zero fuel, for which certification is requested.

(b) Configurations with any likely ice mass accumulations on unprotected surfaces for airplanes approved for operation in icing conditions.

(c) All normal combinations of autopilot, yaw damper, or other automatic flight control systems.

(d) All possible engine settings and combinations of settings from idle power to maximum available thrust including the conditions of one engine stopped and windmilling, in order to address the influence of gyroscopic loads and thrust on aeroelastic stability.

(2) Failures, Malfunctions. and Adverse Conditions. The following conditions should be investigated for aeroelastic instability within the fail-safe envelope defined in paragraph 5a(3) above.

(a) Any critical fuel loading conditions, not shown to be extremely improbable, which may result from mismanagement of fuel.

(b) Any single failure in any flutter control system.

(c) For airplanes not approved for operation in icing conditions, any likely ice accumulation expected as a result of an inadvertent encounter. For airplanes approved for operation in icing conditions, the maximum likely ice accumulation expected as the result of any single failure in the de-icing system, or any combination of failures not shown to be extremely improbable.

(d) Failure of any single element of the structure supporting any engine, independently mounted propeller shaft, large auxiliary power unit, or large externally mounted aerodynamic body (such as an external fuel tank).

(e) For airplanes with engines that have propellers or large rotating devices capable of significant dynamic forces, any single failure of the engine structure that would reduce the rigidity of the rotational axis.

(f) The absence of aerodynamic or gyroscopic forces resulting from the most adverse combination of feathered propellers or other rotating devices capable of significant dynamic forces. In addition, the effect of a single feathered propeller or rotating device must be coupled with the failures of paragraphs 5b(2)(d) and 5b(2)(e) above.

(g) Any single propeller or rotating device capable of significant dynamic forces rotating at the highest likely overspeed.

(h) Any damage or failure condition, required or selected for investigation by § 25.571. The single structural failures described in paragraphs 5b(2)(d) and 5b(2)(e) above need not be considered in showing compliance with this paragraph if;

1 The structural element could not fail due to discrete source damage resulting from the conditions described in § 25.571(e); and

2 A damage tolerance investigation in accordance with § 25.571(b) shows that the maximum extent of damage assumed for the purpose of residual strength evaluation does not involve complete failure of the structural element.

(i) Any damage, failure or malfunction, considered under §§ 25.631, 25.671, 25.672, and 25.1309. This includes the condition of two or more engines stopped or windmilling for the design range of fuel and payload combinations, including zero fuel.

(j) Any other combination of failures, malfunctions, or adverse conditions not shown to be extremely improbable.

c. Detail Design Requirements.

(1) Main surfaces, such as wings and stabilizers, should be designed to meet the aeroelastic stability criteria for nominal conditions and should be investigated for meeting fail-safe criteria by considering stiffness changes due to discrete damage or by reasonable parametric variations of design values.

(2) Control surfaces, including tabs, should be investigated for nominal conditions and for failure modes that include single structural failures (such as actuator disconnects, hinge failures, or, in the case of aerodynamic balance panels, failed seals), single and dual hydraulic system failures and any other combination of failures not shown to be extremely improbable. Where other structural components contribute to the

aeroelastic stability of the system, failures of those components should be considered for possible adverse effects.

(3) Where aeroelastic stability relies on control system stiffness and/or damping, additional conditions should be considered. The actuation system should continuously provide, at least, the minimum stiffness or damping required for showing aeroelastic stability without regard to probability of occurrence for:

(a) More than one engine stopped or windmilling,

(b) Any discrete single failure resulting in a change of the structural modes of vibration (for example; a disconnect or failure of a mechanical element, or a structural failure of a hydraulic element, such as a hydraulic line, an actuator, a spool housing or a valve),

(c) Any damage or failure conditions considered under §§ 25.571, 25.631 and 25.671.

The actuation system minimum requirements should also be continuously met after any combination of failures not shown to be extremely improbable (occurrence less than 10^{-9} per flight hour). However, certain combinations of failures, such as dual electric or dual hydraulic system failures, or any single failure in combination with any probable electric or hydraulic system failure (§ 25.671), are not normally considered extremely improbable regardless of probability calculations. The reliability assessment should be part of the substantiation documentation. In practice, meeting the above conditions may involve design concepts such as the use of check valves and accumulators, computerized pre-flight system checks and shortened inspection intervals to protect against undetected failures.

(4) Consideration of free play may be incorporated as a variation in stiffness to assure adequate limits are established for wear of components such as control surface actuators, hinge bearings, and engine mounts in order to maintain aeroelastic stability margins.

(5) If balance weights are used on control surfaces, their effectiveness and strength, including that of their support structure, should be substantiated.

(6) The automatic flight control system should not interact with the airframe to produce an aeroelastic instability. When analyses indicate possible adverse coupling, tests should be performed to determine the dynamic characteristics of actuation systems such as servo-boost, fully powered servo-control systems, closed-loop airplane flight control systems, stability augmentation systems, and other related powered-control systems.

6. COMPLIANCE. Demonstration of compliance with aeroelastic stability requirements for an airplane configuration may be shown by analyses, tests, or some combination thereof. In most instances, analyses are required to determine aeroelastic stability margins for normal operations, as well as for possible failure conditions. Wind tunnel flutter model tests, where applicable, may be used to supplement flutter analyses. Ground testing may be used to collect stiffness or modal data for the airplane or components. Flight testing may be used to demonstrate compliance of the airplane design throughout the design speed envelope.

a. Analytical Investigations. Analyses should normally be used to investigate the aeroelastic stability of the airplane throughout its design flight envelope and as expanded by the required speed margins. Analyses are used to evaluate aeroelastic stability sensitive parameters such as aerodynamic coefficients, stiffness and mass distributions, control surface balance requirements, fuel management schedules, engine/store locations, and control system characteristics. The sensitivity of most critical parameters may be determined analytically by varying the parameters from nominal. These investigations are an effective way to account for the operating conditions and possible failure modes which may have an effect on aeroelastic stability margins, and to account for uncertainties in the values of parameters and expected variations due to in-service wear or failure conditions.

(1) Analytical Modeling. The following sections discuss acceptable, but not the only, methods and forms of modeling airplane configurations and/or components for purposes of aeroelastic stability analysis. The types of investigations generally encountered in the course of airplane aeroelastic stability substantiation are also discussed. The basic elements to be modelled in aeroelastic stability analyses are the elastic, inertial, and aerodynamic characteristics of the system. The degree of complexity required in the modeling, and the degree to which other characteristics need to be included in the modeling, depend upon the system complexity.

(a) Structural Modeling. Most forms of structural modeling can be classified into two main categories: (1) modeling using a lumped mass beam, and (2) finite element modeling. Regardless of the approach taken for structural modeling, a minimum acceptable level of sophistication, consistent with configuration complexity, is necessary to satisfactorily represent the critical modes of deformation of the primary structure and control surfaces. The model should reflect the support structure for the attachment of control surface actuators, flutter dampers, and any other elements for which stiffness is important in prevention of aeroelastic instability. Wing-pylon mounted engines are often significant to aeroelastic stability and warrant particular attention in the modeling of the pylon, and pylon-engine and pylon-wing interfaces. The model should include the effects of cut-outs, doors, and other structural features which may tend to affect the resulting structural effectiveness. Reduced stiffness should be considered in the modeling of airplane structural components which may exhibit some change in stiffness under limit design flight conditions. Structural models include mass distributions as well as representations of stiffness and possibly damping characteristics. Results from the models should be compared to test data, such as that obtained from ground vibration tests, in order to determine the accuracy of the model and its applicability to the aeroelastic stability investigation.

(b) Aerodynamic Modeling.

1 Aerodynamic modeling for aeroelastic stability requires the use of unsteady, two-dimensional strip or three-dimensional panel theory methods for incompressible or compressible flow. The choice of the appropriate technique depends on the complexity of the dynamic structural motion of the surfaces under investigation and the flight speed envelope of the airplane. Aerodynamic modeling should be supported by tests or previous experience with applications to similar configurations.

2 Main and control surface aerodynamic data are commonly adjusted by weighting factors in the aeroelastic stability solutions. The weighting factors for steady flow (k=0) are usually obtained by comparing wind tunnel test results with theoretical data. Special attention should be given to control surface aerodynamics because viscous and other effects may require more extensive adjustments to theoretical coefficients. Main surface aerodynamic loading due to control surface deflection should be considered.

(2) Types of Analyses.

(a) Oscillatory (flutter) and non-oscillatory (divergence and control reversal) aeroelastic instabilities should be analyzed to show compliance with § 25.629.

(b) The flutter analysis methods most extensively used involve the modal analysis with unsteady aerodynamic forces derived from various two- and three-dimensional theories. These methods are generally for linear systems. Analyses involving control system characteristics should include equations describing system control laws in addition to the equations describing the structural modes.

(c) Airplane lifting surface divergence analyses should include all appropriate rigid body mode degrees-of-freedom since divergence may occur for a structural mode or the short period mode.

(d) Loss of control effectiveness (control reversal) due to the effects of elastic deformations should be investigated. Analyses should include the inertial, elastic, and aerodynamic forces resulting from a control surface deflection.

(3) Damping Requirements.

(a) There is no intent in this AC to define a flight test level of acceptable minimum damping.

(b) Flutter analyses results are usually presented graphically in the form of frequency versus velocity (V-f, Figure 2) and damping versus velocity (V-g, Figures 3 and 4) curves for each root of the flutter solution.

(c) Figure 3 details one common method for showing compliance with the requirement for a proper margin of damping. It is based on the assumption that the structural damping available is 0.03 (1.5% critical viscous damping) and is the same for all modes as depicted by the V-g curves shown in Figure 3. No significant mode, such as curves (2) or (4), should cross the g=0 line below V_D or the g=0.03 line below 1.15 V_D. An exception may be a mode exhibiting damping characteristics similar to curve (1) in Figure 3, which is not critical for flutter. A divergence mode, as illustrated by curve (3) where the frequency approaches zero, should have a divergence velocity not less than 1.15 V_D.

(d) Figure 4 shows another common method of presenting the flutter analysis results and defining the structural damping requirements. An appropriate amount of structural damping for each mode is entered into the analysis prior to the flutter solution. The amount of structural damping used should be supported by measurements taken during full scale tests. This results in modes offset from the g=0 line at zero airspeed and, in some cases, flutter solutions different from those obtained with no structural damping. The similarity in the curves of Figures 3 and 4 are only for simplifying this example. The minimum acceptable damping line applied to the analytical results as shown in Figure 4 corresponds to 0.03 or the modal damping available at zero airspeed for the particular mode of interest, whichever is less, but in no case less than 0.02. No significant mode should cross this line below V_D or the g=0 line below 1.15 V_D.

(e) For analysis of failures, malfunctions or adverse conditions being investigated, the minimum acceptable damping level obtained analytically would be determined by use of either method above, but with a substitution of V_C for V_D and the fail-safe envelope speed at the analysis altitude as determined by 5a(3) above.

FIGURE 2. FREQUENCY VERSUS VELOCITY

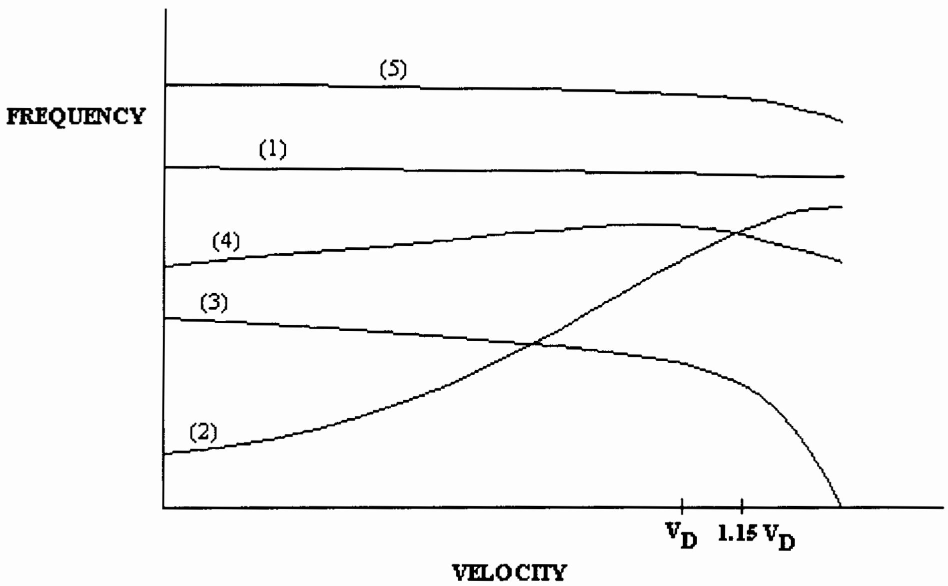


FIGURE 3. DAMPING VERSUS VELOCITY - Method 1

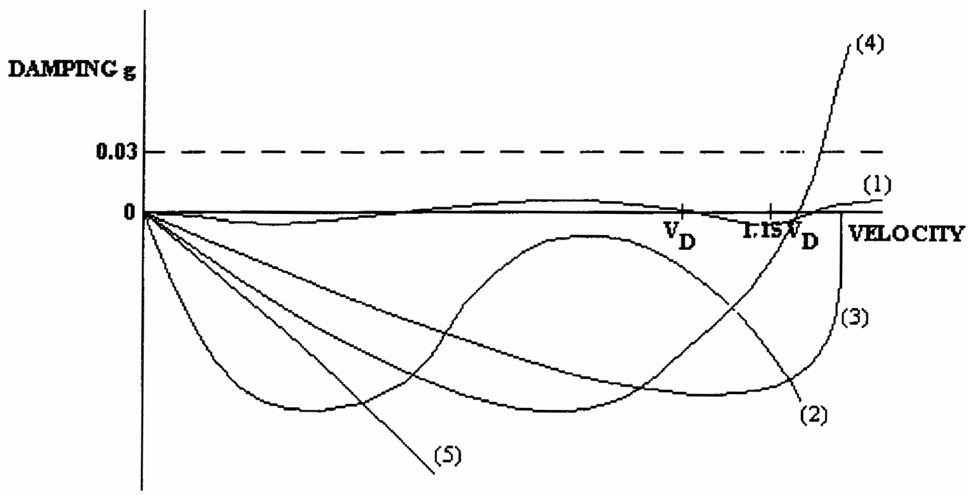
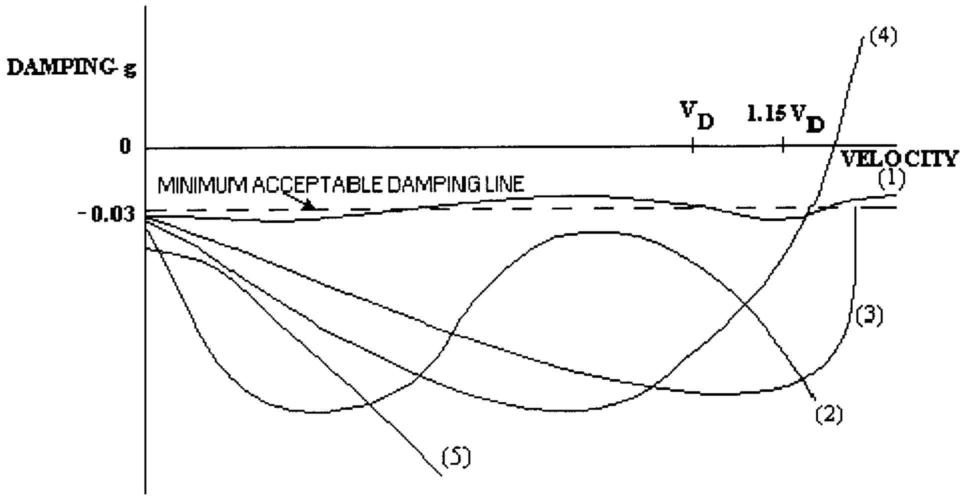


FIGURE 4. DAMPING VERSUS VELOCITY - Method 2



(4) Analysis Considerations. Airframe aeroelastic stability analyses may be used to verify the design with respect to the structural stiffness, mass, fuel (including in-flight fuel management), automatic flight control system characteristics, and altitude and Mach number variations within the design flight envelope. The complete airplane should be considered as composed of lifting surfaces and bodies, including all primary control surfaces which can interact with the lifting surfaces to affect flutter stability. Control surface flutter can occur in any speed regime and has historically been the most common form of flutter. Lifting surface flutter is more likely to occur at high dynamic pressure and at high subsonic and transonic Mach numbers. Analyses are necessary to establish the mass balance and/or stiffness and redundancy requirements for the control surfaces and supporting structure and to determine the basic surface flutter trends. The analyses may be used to determine the sensitivity of the nominal airplane design to aerodynamic, mass, and stiffness variations. Sources of stiffness variation may include the effects of skin buckling at limit load factor, air entrapment in hydraulic actuators, expected levels of in-service free play, and control system components which may include elements with nonlinear stiffness. Mass variations include the effects of fuel density and distribution, control surface repairs and painting, and water and ice accumulation.

(a) Control Surfaces. Control surface aeroelastic stability analyses should include control surface rotation, tab rotation (if applicable), significant modes of the airplane, control surface torsional degrees-of-freedom, and control surface bending (if applicable). Analyses of airplanes with tabs should include tab rotation that is both independent and related to the parent control surface. Control surface rotation frequencies should be varied about nominal values as appropriate for the condition. The control surfaces should be analysed as completely free in rotation unless it can be shown that this condition is extremely improbable. All conditions between stick-free and stick-fixed should be investigated. Freeplay effects should be incorporated to account for any influence of in-service wear on flutter margins. The aerodynamic coefficients of the control surface and tab used in the aeroelastic stability analysis should be adjusted to match experimental values at zero frequency. Once the analysis has been conducted with the nominal, experimentally adjusted values of hinge moment coefficients, the analysis should be conducted with parametric variations of these coefficients and other parameters subject to variability. If aeroelastic stability margins are found to be sensitive to these parameters, then additional verification in the form of model or flight tests may be required.

(b) Mass Balance.

1 The magnitude and spanwise location of control surface balance weights may be evaluated by analysis and/or wind tunnel flutter model tests. If the control surface torsional degrees of freedom are not included in the analysis, then adequate separation must be maintained between the frequency of the control surface first torsion mode and the flutter mode.

2 Control surface unbalance tolerances should be specified to provide for repair and painting. The accumulation of water, ice, and/or dirt in or near the trailing edge of a control surface should be avoided. Free play between the balance weight, the support arm, and the control surface must not be allowed. Control surface mass properties (weight and static unbalance) should be confirmed by measurement before ground vibration testing.

3 The balance weights and their supporting structure should be substantiated for the extreme load factors expected throughout the design flight envelope. In the absence of a rational investigation, the following limit accelerations, applied through the balance weight center of gravity should be used.

100g normal to the plane of the surface
30g parallel to the hinge line
30g parallel to the plane of the surface and perpendicular to the hinge line

(c) Passive Flutter Dampers. Control surface passive flutter dampers may be used to prevent flutter in the event of failure of some element of the control surface actuation system or to prevent control surface buzz. Flutter analyses and/or flutter model wind tunnel tests may be used to verify adequate damping. Damper support structure flexibility should be included in the determination of adequacy of damping at the flutter frequencies. Any single damper failure should be considered. Combinations of multiple damper failures should be examined when not shown to be extremely improbable. The combined free play of the damper and supporting elements between the control surface and fixed surfaces should be considered. Provisions for in-service checks of damper integrity should be considered. Refer to paragraph 5c(3) above for conditions to consider where a control surface actuator is switched to the role of an active or passive damping element of the flight control system.

(d) Intersecting Lifting Surfaces. Intersecting lifting surface aeroelastic stability characteristics are more difficult to predict accurately than the characteristics of planar surfaces such as wings. This is due to difficulties both in correctly predicting vibration modal characteristics and in assessing those aerodynamic effects which may be of second order importance on planar surfaces, but are significant for intersecting surfaces. Proper representation of modal deflections and unsteady aerodynamic coupling terms between surfaces is essential in assessing the aeroelastic stability characteristics. The in-plane forces and motions of one or the other of the intersecting surfaces may have a strong effect on aeroelastic stability; therefore, the analysis should include the effects of steady flight forces and elastic deformations on the in-plane effects.

(e) Ice Accumulation. Aeroelastic stability analysis should use the mass distributions derived from the maximum likely ice accumulations. The ice accumulation determination can take into account the ability to detect the ice and the time required to leave the icing condition. The analyses need not consider the aerodynamic effects of ice shapes.

(f) Whirl Flutter.

1 The evaluation of the aeroelastic stability should include investigations of any significant elastic, inertial, and aerodynamic forces, including those associated with rotations and displacements in the plane of any turbofan or propeller, including propeller or fan blade aerodynamics, powerplant flexibilities, powerplant mounting characteristics, and gyroscopic coupling.

2 Failure conditions are usually significant for whirl instabilities. Engine mount, engine gear box support, or shaft failures which result in a node line shift for propeller hub pitching or yawing motion are especially significant.

3 A wind tunnel test with a component flutter model, representing the engine/propeller system and its support system along with correlative vibration and flutter analyses of the flutter model, may be used to demonstrate adequate stability of the nominal design and failed conditions.

(g) Automatic Control Systems. Aeroelastic stability analyses of the basic configuration should include simulation of any control system for which interaction may exist between the sensing elements and the structural modes. Where structural/control system feedback is a potential problem the effects of servo-actuator characteristics and the effects of local deformation of the servo mount on the feedback sensor output should be included in the analysis. The effect of control system failures on the airplane aeroelastic stability characteristics should be investigated. Failures which significantly affect the system gain and/or phase and are not shown to be extremely improbable should be analysed.

b. Testing. The aeroelastic stability certification test program may consist of ground tests, flutter model tests, and flight flutter tests. Ground tests may be used for assessment of component stiffness and for determining the vibration modal characteristics of airplane components and the complete airframe. Flutter model testing may be used to establish flutter trends and validate aeroelastic stability boundaries in areas where unsteady aerodynamic calculations require confirmation. Full scale flight flutter testing provides final verification of aeroelastic stability. The results of any of these tests may be used to provide substantiation data, to verify and improve analytical modeling procedures and data, and to identify potential or previously undefined problem areas.

(1) Structural Component Tests. Stiffness tests or ground vibration tests of structural components are desirable to confirm analytically predicted characteristics and are necessary where stiffness calculations cannot accurately predict these characteristics. Components should be mounted so that the mounting characteristics are well defined or readily measurable.

(2) Control System Component Tests. When reliance is placed on stiffness or damping to prevent aeroelastic instability, the following control system tests should be conducted. If the tests are performed off the airplane the test fixtures should reflect local attachment flexibility.

(a) Actuators for primary flight control surfaces and flutter dampers should be tested with their supporting structure. These tests are to determine the actuator/support structure stiffness for nominal design and failure conditions considered in the fail-safe analysis.

(b) Flutter damper tests should be conducted to verify the impedance of damper and support structure. Satisfactory installed damper effectiveness at the potential flutter frequencies should, however, be assured. The results of these tests can be used to determine a suitable, in-service maintenance schedule and replacement life of the damper. The effects of allowable in-service free play should be measured.

(3) Ground Vibration Tests.

(a) Ground vibration tests (GVT) or modal response tests are normally conducted on the complete conforming airplane. A GVT may be used to check the mathematical structural model. Alternatively, the use of measured modal data alone in aeroelastic stability analyses, instead of analytical modal data modified to match test data, may be acceptable provided the accuracy and completeness of the measured modal data is established. Whenever structural modifications or inertia changes are made to a previously certified design or a GVT validated model of the basic airplane, a GVT may not be necessary if these changes are shown not to affect the aeroelastic stability characteristics.

(b) The airplane is best supported such that the suspended airplane rigid body modes are effectively uncoupled from the elastic modes of the airplane. Alternatively, a suspension method may be used that couples with the elastic airplane provided that the suspension can be analytically de-coupled from the airplane structure in the vibration analysis. The former suspension criterion is preferred for all ground vibration tests and is necessary in the absence of vibration analysis.

(c) The excitation method needs to have sufficient force output and frequency range to adequately excite all significant resonant modes. The effective mass and stiffness of the exciter and attachment hardware should not distort modal response. More than one exciter or exciter location may be necessary to insure that all significant modes are identified. Multiple exciter input may be necessary on structures with significant internal damping to avoid low response levels and phase shifts at points on the structure distant from the point of excitation. Excitation may be sinusoidal, random, pseudo-random, transient, or other short duration, non stationary means. For small surfaces the effect of test sensor mass on response frequency should be taken into consideration when analyzing the test results.

(d) The minimum modal response measurement should consist of acceleration (or velocity) measurements and relative phasing at a sufficient number of points on the airplane structure to accurately describe the response or mode shapes of all significant structural modes. In addition, the structural damping of each mode should be determined.

(4) Flutter Model Tests.

(a) Dynamically similar flutter models may be tested in the wind tunnel to augment the flutter analysis. Flutter model testing can substantiate the flutter margins directly or indirectly by validating analysis data or methods. Some aspects of flutter analysis may require more extensive validation than others, for example control surface aerodynamics, T-tails and other configurations with aerodynamic interaction and compressibility effects. Flutter testing may additionally be useful to test configurations that are impractical to verify in flight test, such as fail-safe conditions or extensive store configurations. In any such testing, the mounting of the model and the associated analysis should be appropriate and consistent with the study being performed.

(b) Direct substantiation of the flutter margin (clearance testing) implies a high degree of dynamic similitude. Such a test may be used to augment an analysis and show a configuration flutter free throughout the expanded design envelope. All the physical parameters which have been determined to be significant for flutter response should be appropriately scaled. These will include elastic and inertia properties, geometric properties and dynamic pressure. If transonic effects are important, the Mach number should be maintained.

(c) Validation of analysis methods is another appropriate use of wind tunnel flutter testing. When the validity of a method is uncertain, correlation of wind tunnel flutter testing results with a corresponding analysis may increase confidence in the use of the analytical tool for certification analysis. A methods validation test should simulate conditions, scaling and geometry appropriate for the intended use of the analytical method.

(d) Trend studies are an important use of wind tunnel flutter testing. Parametric studies can be used to establish trends for control system balance and stiffness, fuel and payload variations, structural compliances and configuration variations. The set of physical parameters requiring similitude may not be as extensive to study parametric trends as is required for clearance testing. For example, an exact match of the Mach number may not be required to track the effects of payload variations on a transonic airplane.

(5) <u>Flight Flutter Tests</u>.

(a) Full scale flight flutter testing of an airplane configuration to V_{DF}/M_{DF} is a necessary part of the flutter substantiation. An exception may be made when aerodynamic, mass, or stiffness changes to a certified airplane are minor, and analysis or ground tests show a negligible effect on flutter or vibration characteristics. If a failure, malfunction, or adverse condition is simulated during a flight test, the maximum speed investigated need not exceed V_{FC}/M_{FC} if it is shown, by correlation of the flight test data with other test data or analyses, that the requirements of § 25.629(b)(2) are met.

(b) Airplane configurations and control system configurations should be selected for flight test based on analyses and, when available, model test results. Sufficient test conditions should be performed to demonstrate aeroelastic stability throughout the entire flight envelope for the selected configurations.

(c) Flight flutter testing requires excitation sufficient to excite the modes shown by analysis to be the most likely to couple for flutter. Excitation methods may include control surface motions or internal moving mass or external aerodynamic exciters or flight turbulence. The method of excitation must be appropriate for the modal response frequency being investigated. The effect of the excitation system itself on the airplane flutter characteristics should be determined prior to flight testing.

(d) Measurement of the response at selected locations on the structure should be made in order to determine the response amplitude, damping and frequency in the critical modes at each test airspeed. It is desirable to monitor the response amplitude, frequency and damping change as V_{DF}/M_{DF} is approached. In demonstrating that there is no large and rapid damping reduction as V_{DF}/M_{DF} is approached, an endeavor should be made to identify a clear trend of damping versus speed. If this is not possible, then sufficient test points should be undertaken to achieve a satisfactory level of confidence that there is no evidence of an adverse trend.

(e) An evaluation of phenomena not presently amenable to analyses, such as shock effects, buffet response levels, vibration levels, and control surface buzz, should also be made during flight testing.

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